

# Solar neutrino limit on axions and keV-mass bosons

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The all-flavor solar neutrino flux measured by the Sudbury Neutrino Observatory (SNO) constrains nonstandard energy losses to less than about 10% of the Sun's photon luminosity, superseding a helioseismological argument and providing new limits on the interaction strength of low-mass particles. For the axion-photon coupling strength we find  $g_{a\gamma} < 7 \times 10^{-10} \text{ GeV}^{-1}$ . We also derive explicit limits on the Yukawa coupling to electrons of pseudoscalar, scalar and vector bosons with keV-scale masses.

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## I. INTRODUCTION

The interaction strength of new low-mass particles with photons, electrons or nucleons is severely constrained by the well-known requirement that stars not lose energy in excess of observational constraints [1, 2, 3]. Depending on the assumed particle mass and interaction structure, the most restrictive limits typically derive from population statistics in globular clusters, the white dwarf luminosity function, and the duration of the SN 1987A neutrino signal. Such constraints usually imply that the solar particle emission is small compared to its photon luminosity, but it can still serve as a powerful source, e.g. for the ongoing solar axion searches [4, 5, 6, 7].

Constraints based on the properties of the Sun remain of interest, even if they are less restrictive than other astrophysical arguments, because they are more direct and thus perhaps more comparable to laboratory experiments. Moreover, sometimes the Sun is enough to test a given hypothesis. In this case it is nice to have a simple argument at hand that does not require more complicated astrophysical reasoning.

Previously the most sensitive diagnostic for the solar interior was the helioseismological sound-speed profile, providing restrictive energy-loss limits [8]. Of course, the underlying chain of arguments is not simple and worse, a new determination of the solar element abundances [9] has created an unresolved tension between solar modeling and helioseismology [10, 11]. While the conservative limit of Ref. [8] likely remains unchanged, it is nice that the measured solar neutrino flux provides a somewhat more restrictive limit based on a simpler argument.

The recently completed SNO measurements of the all-flavor solar neutrino flux [12, 13, 14] probe directly the physical conditions of the particle-emitting solar core. The steep temperature dependence of the  $^8\text{B}$  neutrino production rate provides a sensitive test of the Sun's interior that would be hotter if a lot of "invisible energy" were produced. The main purpose of our note is to update the solar energy-loss constraints using the SNO results.

The inner solar temperature is around 1 keV, so these limits always apply to sub-keV mass particles, notably

axions. Recently the hypothesis of keV-scale bosons as possible dark matter candidates has received some attention [15]. Moreover, some time ago it was proposed [16] that keV-mass pseudoscalars explain the annual modulation observed in the DAMA/Libra experiment [17]. Unfortunately, this intriguing interpretation was based on the incorrect axio-electric absorption rate of Refs. [16, 18], the correct rate being much larger but nearly independent of velocity [15]. While an earlier version of our manuscript was largely motivated by this now-dismissed interpretation, an evaluation of the solar limit for keV-mass bosons may still prove useful in future.

We present the new solar energy-loss constraint in the context of axions and apply it explicitly to the axion-photon interaction strength. This result is of interest for solar axion searches. We also treat explicitly keV-mass bosons  $\chi$  that couple to electrons. To this end we re-derive the  $\gamma + e^- \rightarrow e^- + \chi$  Compton cross section, correcting several errors in the literature.

## II. AXION-PHOTON INTERACTION

Axions are of particular interest because the Sun is used as a source for ongoing helioscope searches [4, 5, 6, 7]. Axions are produced by the Primakoff process  $\gamma + Ze \rightarrow Ze + a$ , that is mediated by a virtual photon due to the axion's two photon interaction  $\mathcal{L}_{a\gamma} = -\frac{1}{4}g_{a\gamma}F_{\mu\nu}\tilde{F}^{\mu\nu}a = g_{a\gamma}\mathbf{E} \cdot \mathbf{B}a$ . In the laboratory, solar axions convert back into X-rays while traveling along a dipole magnet oriented toward the Sun. For  $m_a \lesssim 0.2 \text{ eV}$ , CAST [6] provides the most restrictive limit of  $g_{10} < 0.88$  at 95% CL, where  $g_{10} = g_{a\gamma}/10^{-10} \text{ GeV}^{-1}$ . The stellar energy-loss limit from globular-cluster stars is comparable, but without a detailed budget of systematic uncertainties.

The axion luminosity  $L_a = g_{10}^2 1.85 \times 10^{-3} L_\odot$  [6] represents a negligible perturbation of the Sun if  $g_{10}$  is below the CAST limit. However, for larger couplings the energy loss modifies the solar structure. To maintain the observed amount of energy emitted at the surface, more energy than usual needs to be produced by nuclear burning. The latter is self-regulating, so the energy-producing re-

gions must heat up. The extra losses would have operated for the entire lifetime of the Sun so that one must evolve a zero-age model to its present age of  $4.6 \times 10^9$  years, at which point it must match the present-day radius and surface luminosity. One adjusts the unknown pre-solar helium abundance to achieve this fit.

Schlattl et al. (1998) have produced a series of such self-consistent present-day solar models for different levels of axion emission based on the Primakoff effect [8]. They provide the required pre-solar helium abundance and show the present-day central helium abundance, density and temperature as well as the neutrino fluxes. In 1998 the question of neutrino flavor oscillations was not yet settled. Therefore, Schlattl et al. used helioseismology to provide a conservative constraint  $L_a < 0.20 L_\odot$ , corresponding to  $g_{10} \lesssim 10$ .

The all-flavor solar neutrino flux from the  $^8\text{B}$  reaction measured by the SNO experiment [12, 13, 14] is a more direct probe. For  $L_a \lesssim 0.5 L_\odot$  the self-consistent solar models of Schlattl et al. [8] provide with excellent accuracy

$$\Phi_{\text{B}8}^a = \Phi_{\text{B}8}^0 \left( \frac{L_\odot + L_a}{L_\odot} \right)^{4.6}, \quad (1)$$

$$T_c^a = T_c^0 \left( \frac{L_\odot + L_a}{L_\odot} \right)^{0.22}, \quad (2)$$

where  $\Phi_{\text{B}8}^a$  is the  $^8\text{B}$  solar neutrino flux for a solar model with axion losses  $L_a$  whereas  $\Phi_{\text{B}8}^0$  is for the standard case, and similar for the central temperature  $T_c$ .

These power laws follow from a simple scaling argument because we are in a regime where the axion flux is a small perturbation. The second equation shows that energy generation by hydrogen burning for solar conditions scales approximately with  $T^{4.5}$  and the  $^8\text{B}$  flux varies roughly as  $T^{18}$ . The main advantage of Eq. (1) is that it uses the constraint of a self-consistent present-day solar model and that one has a direct connection between the Sun-averaged neutrino and axion fluxes.

The all-flavor solar neutrino flux from the  $^8\text{B}$  reaction was measured by SNO. The pure  $\text{D}_2\text{O}$  phase provided a flux of  $5.09_{-0.43}^{+0.44}(\text{stat})_{-0.43}^{+0.46}(\text{sys})$  in units of  $10^6 \text{ cm}^{-2} \text{ s}^{-1}$  [12]. The salt phase provided  $4.94_{-0.21}^{+0.21}(\text{stat})_{-0.34}^{+0.38}(\text{sys})$  [13]. Very recently, the  $^3\text{He}$  phase gave  $5.54_{-0.31}^{+0.33}(\text{stat})_{-0.34}^{+0.36}(\text{sys})$  [14]. The old solar models predicted 5.94 in the same units, whereas the new opacities lead to 4.72, each with a nominal  $1\sigma$  error of 11% [11]. The main non-abundance contributions to this uncertainty are opacity (6.8%), diffusion (4.2%) and the  $S_{17}$  factor for the  $p + ^7\text{Be}$  reaction (3.8%).

The measurements and predictions agree well within the stated errors, although the dominant uncertainty of the calculated fluxes evidently is from the assumed element abundances. It appears reasonably conservative to assume the true neutrino flux does not exceed the prediction by more than 50% so that

$$L_a < 0.1 L_\odot. \quad (3)$$

This nominal limit implies

$$g_{a\gamma} < 7 \times 10^{-10} \text{ GeV}^{-1}, \quad (4)$$

somewhat more restrictive than the helioseismological limit. The Tokyo helioscope search provides a limit very similar to this result [4, 5], whereas the CAST search is significantly more sensitive [6, 7] and therefore self-consistent: An axion flux on the level of the CAST limit would not cause any other observable modification of the Sun or of the solar neutrino flux.

The sensitivity of the helioscope technique quickly diminishes for  $m_a \gtrsim 1 \text{ eV}$ . An alternative is Bragg conversion in the strong electric field within a crystal lattice. This approach extends to keV-scale masses because the spatial  $E$ -field variation in the crystal provides the required momentum difference. Constraints on  $g_{a\gamma}$  from such experiments [19, 20, 21, 22, 23] are however less restrictive than the solar limit of Eq. (4). The most recent constraint from the CDMS experiment is  $g_{a\gamma} < 24 \times 10^{-10} \text{ GeV}^{-1}$  at 95% CL for  $m_a < 0.1 \text{ keV}$  [23].

### III. BOSON-ELECTRON COUPLING

The exact energy-loss mechanism is irrelevant for the limit of Eq. (3) even though the spatial distribution of particle emission somewhat depends on the temperature and density variation of the relevant emission process. So we may consider other reactions besides the axion Primakoff process.

A case in point motivated by the hypothesis of keV scale dark matter [15] are bosons  $\chi$  that interact with electrons through a Yukawa coupling  $g_{\chi ee}$ . Such particles are emitted from stars by bremsstrahlung  $e + Ze \rightarrow Ze + e + \chi$  and the Compton process  $\gamma + e \rightarrow e + \chi$ . For pseudoscalars, bremsstrahlung contributes about 75% of the total emission in the Sun, Compton about 25% [25]. However, the energy spectrum for bremsstrahlung is much softer than for Compton. For keV mass particles threshold effects are important, so it is enough to use the Compton process alone.

We have calculated the Compton cross sections for the pseudoscalar (PS), scalar (S), and vector (V) cases for bosons with a nonzero mass  $m_\chi$ . The interaction is

$$\mathcal{L}_{\chi ee} = g_{\chi ee} \times \begin{cases} i\chi\bar{e}\gamma_5 e & \text{PS,} \\ \chi\bar{e}e & \text{S,} \\ \chi_\mu\bar{e}\gamma^\mu e & \text{V.} \end{cases} \quad (5)$$

General expressions for the total Compton cross section are given in the Appendix, superseding for PS an erroneous result in the literature [26].<sup>1</sup> For the application

<sup>1</sup> In Ref. [26] the factors of 2 in the argument of the logarithm in Eq. (A.1) are missing. In an earlier version of our paper we

in the Sun we take the limit of nonrelativistic electrons with mass  $m_e \gg \omega$  (photon energy) and use the velocity of the outgoing  $\chi$  boson  $\beta = \sqrt{1 - (m_\chi/\omega)^2}$  to express the cross sections. For PS we find

$$\sigma_{\text{PS}} = \frac{g_{\chi ee}^2 \alpha}{3m_e^2} \frac{\omega^2}{m_e^2} \frac{\beta(3 + \beta^4)}{4} \quad (6)$$

in agreement with Ref. [15]. This is a superposition of a final-state  $s$  and  $d$  wave. For the other cases we find

$$\sigma = \frac{g_{\chi ee}^2 \alpha}{3m_e^2} \times \begin{cases} \beta^3 & \text{S,} \\ \beta(3 - \beta^2) & \text{V.} \end{cases} \quad (7)$$

For S this is a final-state  $p$  wave, for V a superposition of  $s$  and  $p$ . For a massless  $\chi$  boson we have  $\beta = 1$  and the V cross section is twice that of S, representing 2 interacting spin degrees of freedom. For the other extreme  $\beta \rightarrow 0$  our result reflects 3 interacting degrees of freedom relative to S. In Ref. [15] the V cross section was stated without the velocity factors.

We integrate the emission rate over a standard solar model [27] and find explicitly for  $m_\chi = 0$

$$L_\chi^{\text{Compton}} = g_{ee\chi}^2 \times \begin{cases} 1.25 \times 10^{20} L_\odot & \text{PS,} \\ 1.72 \times 10^{24} L_\odot & \text{S,} \\ 3.44 \times 10^{24} L_\odot & \text{V.} \end{cases} \quad (8)$$

With Eq. (3) this implies the constraints

$$g_{ee\chi} < \begin{cases} 2.8 \times 10^{-11} & \text{PS,} \\ 2.4 \times 10^{-13} & \text{S,} \\ 1.7 \times 10^{-13} & \text{V.} \end{cases} \quad (9)$$

We show the  $m_\chi$  dependence of these limits in Fig. 1.

#### IV. SUMMARY

The SNO measurements of the all-flavor solar neutrino flux produced by the very temperature-dependent  $^8\text{B}$  reaction severely constrain anomalous solar energy losses. We have re-considered self-consistent solar models produced by Schlattl et al. [8] who included axion losses by the Primakoff effect. We have observed that the predicted solar neutrino flux is nicely reproduced by a simple and intuitive power law as a function of the assumed anomalous solar energy loss. In this way the measured neutrino flux and the assumed energy loss are directly related in a simple form. The excellent agreement between the measured and predicted solar neutrino flux provides a restrictive limit on any new energy loss channel of the

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had used this incorrect expression and found a spurious cross-section increase with  $m_\chi$ . Our limits would have excluded the full range of PS parameters explaining the DAMA annual modulation [16], an interpretation that itself was based on a spurious cross section [15].

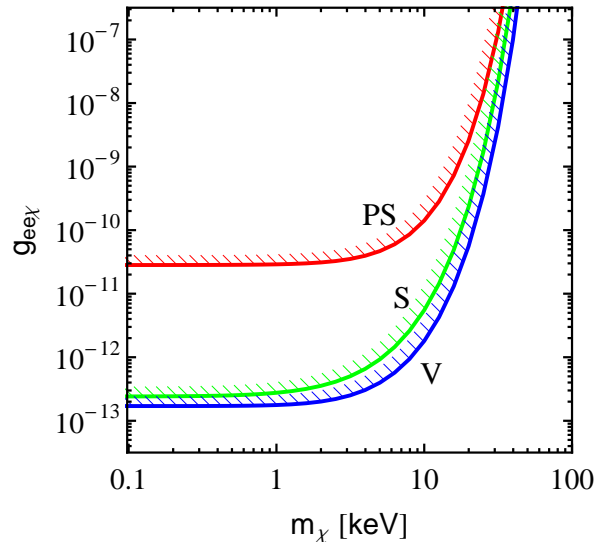


FIG. 1: Mass dependence of the solar  $g_{ee\chi}$  limit. The PS curve supersedes the one in our original preprint that was reproduced in Ref. [24].

Sun. While constraints from other astrophysical arguments are usually more restrictive, the solar neutrino limit on new energy losses is complementary in that it is based on a direct diagnostic of the solar interior.

In particular, we have derived a new solar limit on the axion-photon interaction strength  $g_{a\gamma}$ , superseding an often-cited helioseismological result. Only the CAST experiment is sensitive enough to detect solar axions obeying our new constraint Eq. (4).

For bosons coupling to electrons, our limit extends to masses of almost 10 keV even though the solar inner temperature is around 1 keV. This would have been of interest to constrain the DAMA annual modulation in terms of keV-scale pseudoscalar dark matter particles. However, based on the corrected axio-electric absorption rate of Ref. [15] this interpretation is no longer viable. Instead, recent direct constraints on keV-scale pseudoscalar dark matter by CoGeNT [24] and CDMS [23] are more restrictive than the solar limit.

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## APPENDIX: CROSS SECTIONS

and

For future reference, we list here the complete expressions of the Compton cross sections for the production of massive pseudoscalar, scalar, and vector bosons. We use the notation of Ref. [26], namely  $p_0 = (s - m_e^2 + m_\chi^2)/2\sqrt{s}$ ,  $p = (p_0^2 - m_\chi^2)^{1/2}$ ,  $k_0 = (s + m_e^2)/2\sqrt{s}$ , and  $k = \sqrt{s} - k_0$ . We find

$$\sigma = \frac{\alpha g_{\chi ee}^2}{8s} \frac{p}{k} \left[ A(s) + B(s) \frac{\sqrt{s}}{p} \log \frac{2p_0 k_0 + 2pk - m_\chi^2}{2p_0 k_0 - 2pk - m_\chi^2} \right], \quad (\text{A.1})$$

where

$$A(s) = \begin{cases} -3 + \frac{m_e^2 - m_\chi^2}{s} + \frac{8m_\chi^2 s}{(s - m_e^2)^2}, & \text{PS,} \\ -3 + \frac{m_e^2 - m_\chi^2}{s} + \frac{8(m_\chi^2 - 4m_e^2)s}{(s - m_e^2)^2}, & \text{S,} \\ 2 + \frac{2(m_e^2 - m_\chi^2)}{s} + \frac{16(m_\chi^2 + 2m_e^2)s}{(s - m_e^2)^2}, & \text{V,} \end{cases} \quad (\text{A.2})$$

$$B(s) = \begin{cases} 1 - \frac{2m_\chi^2}{s - m_e^2} + \frac{2m_\chi^2(m_\chi^2 - 2m_e^2)}{(s - m_e^2)^2}, & \text{PS,} \\ 1 + \frac{2(m_\chi^2 - 4m_e^2)}{s - m_e^2} + \frac{2(m_\chi^4 - 6m_\chi^2 m_e^2 + 8m_e^4)}{(s - m_e^2)^2}, & \text{S,} \\ 2 - \frac{4(m_\chi^2 + 2m_e^2)}{s - m_e^2} - \frac{4(4m_e^4 - m_\chi^4)}{(s - m_e^2)^2}, & \text{V.} \end{cases} \quad (\text{A.3})$$

For  $m_\chi = 0$  and  $g_{\chi ee}^2 = 4\pi\alpha$ , the V cross section reduces to the usual Compton cross section for  $\gamma + e \rightarrow e + \gamma$ .

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